Self-Sensing Fiber-Reinforced Composites

PI: Christopher C. Bowland

Oak Ridge National Laboratory

June 3, 2020

2020 DOE Vehicle Technologies Office
Annual Merit Review

Project ID: mat173

Overview

Timeline

- Start Date: October 2019
- End Date: September 2022
- Percent Complete: 25%

Budget

- Total project funding
  - DOE: $300k
  - Industrial cost share: $150k

Partners

- CRADA with Dronesat, LLC
- Project Lead: ORNL

Barriers and Technical Targets

- Critical Challenge for carbon fiber composites: "Joining, NDE, Life Monitoring and Repair"*
- "The ability to predict performance for material, joints, and parts would allow for optimized design while minimizing cost"*
- Structural health monitoring would help inform models for in-service performance prediction

*From "Materials: Materials Technical Team Roadmap" (2017), by U.S. DRIVE Partnership

Relevance

Impact

- Multifunctional composite with structural health monitoring offers:
  - Increased composite safety
  - Improved estimates of maintenance requirements
- The focus is on cargo transportation and infrastructure monitoring, it also opens other markets:
  - Automotive industry (electric automobile battery enclosures and compressed natural gas storage tanks)
  - Oil and natural gas distribution (composite pipelines and pipeline repairs)
  - Infrastructure repair (patches to concrete bridge pillars)
  - Military (unmanned aerial vehicles with extended flight times)
  - Space vehicles (cryogenic fuel tanks)

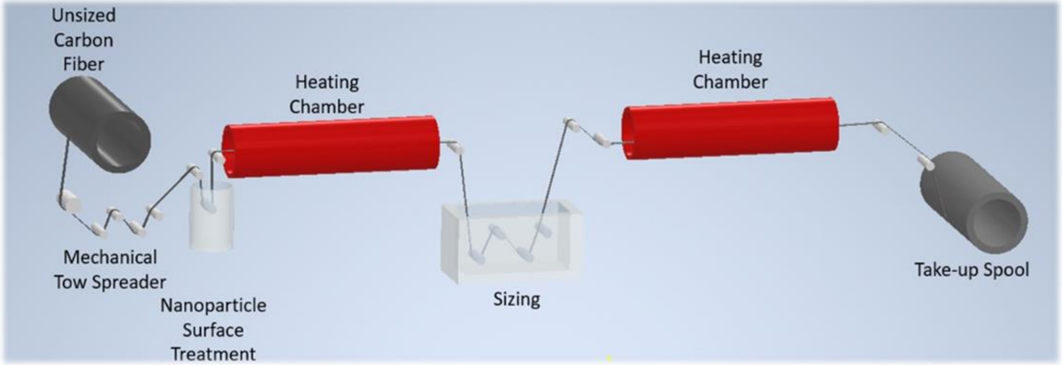
Objectives

- Use a roll-to-roll fiber processing method to add various nanoparticles to the fiber surface
- Demonstrate a scalable, multifunctional composite with in-situ sensing capabilities as well as improved mechanical performance

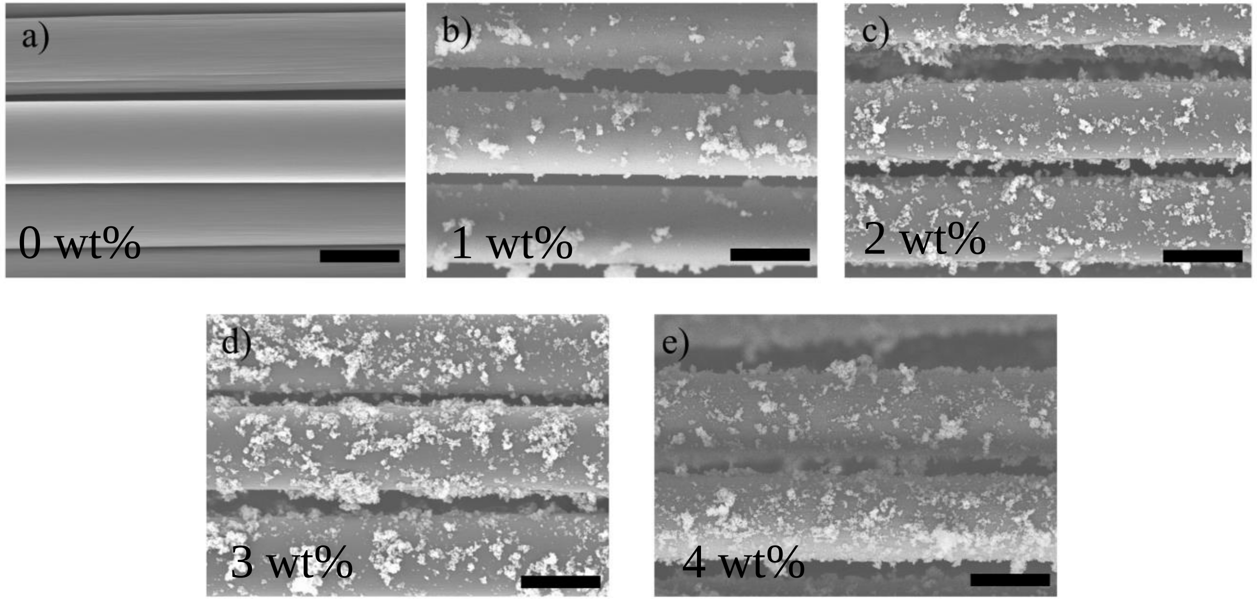
Approach

- Roll-to-roll dip coating deposition process to integrate nanoparticles into the sizing for improved mechanical strength and sensing functionality
  - Concentration of nanoparticles can be easily varied
  - Compatible with many different nanoparticles and fibers
- Use commercially available products combined in a mutually beneficial approach
- Commercially sourced products makes scale-up feasible

Dip coating schematic (fiber processed from the left to the right)



TiO_2 nanoparticle (30 nm) coated carbon fiber



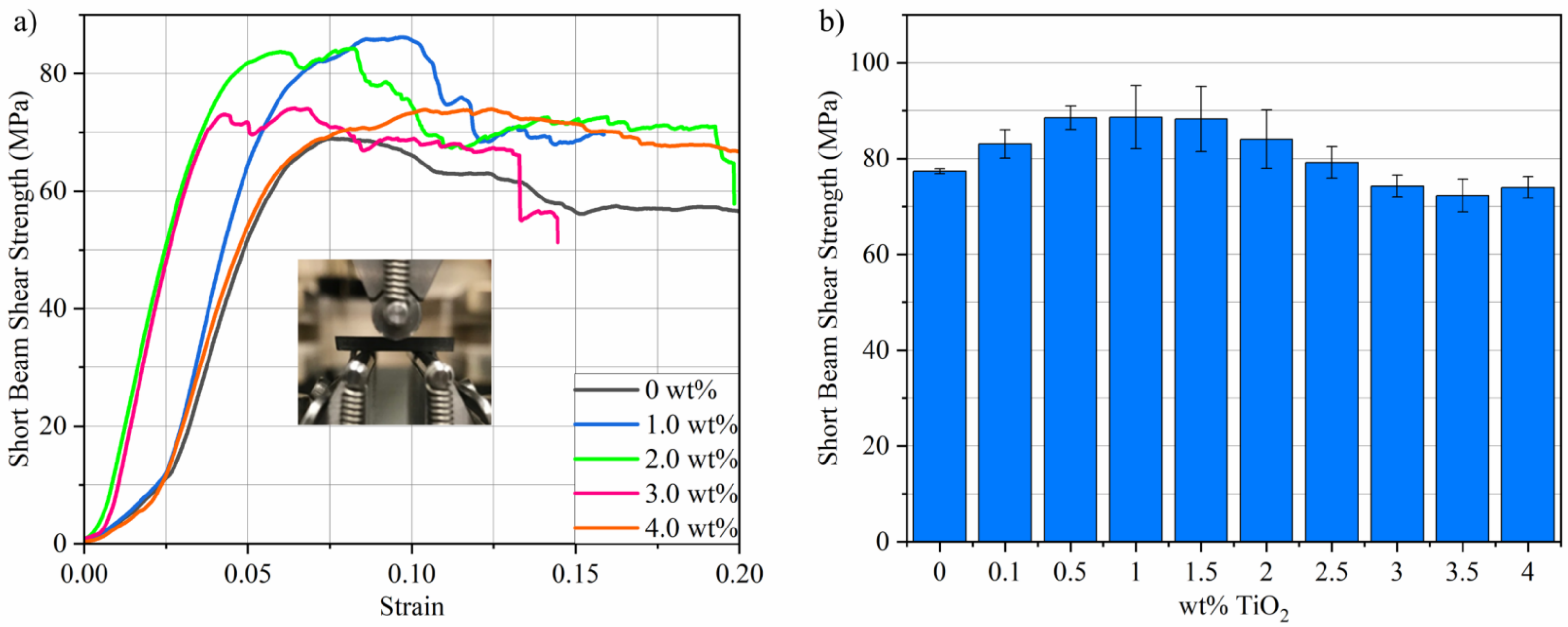
Scale bars are 5 µm

Accomplishments

<u>Interlaminar Shear Strength Testing</u>

- Unidirectional composites were fabricated using a filament winding technique
- Baseline: 77.3 MPa (0 wt% nanoparticles)
- Highest performing composite: 88.7 MPa (1 wt% nanoparticles)
- **Maximum increase of 14.7% increase in interlaminar shear strength so milestone was achieved**

Milestone: Fabricate multifunctional composites and perform mechanical testing (12/31/2019)
Criteria: Short beam shear test should show an interlaminar shear strength improvement of at least 10%

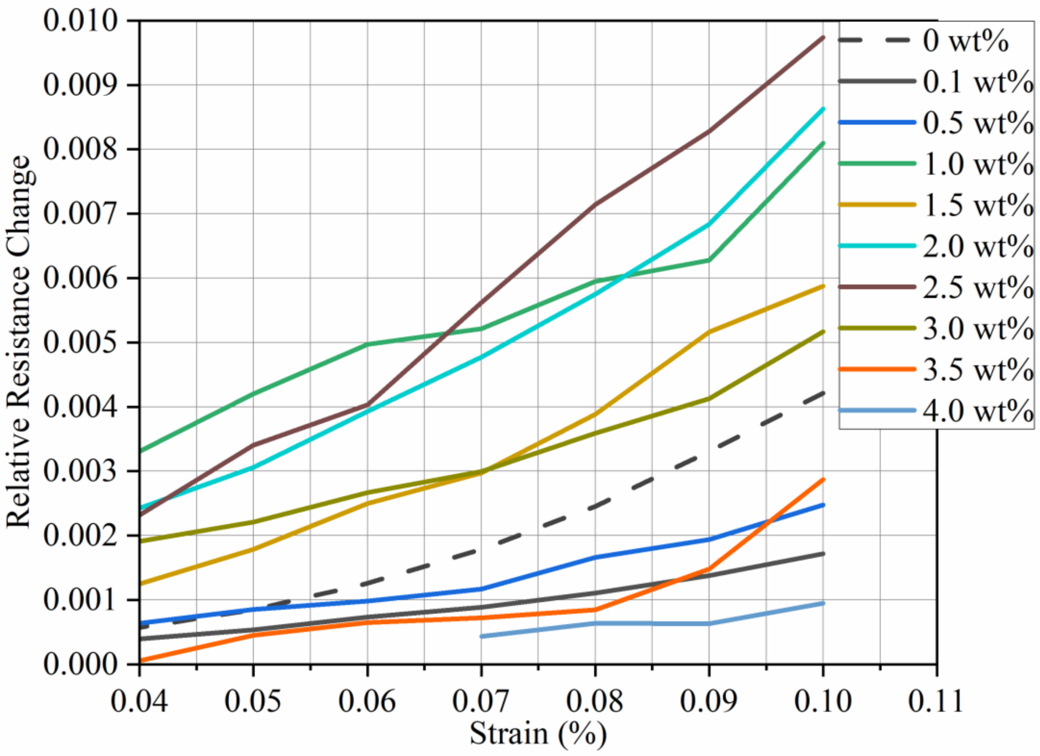


Interlaminar shear strength testing: a) representative stress-strain curves and b) average short-beam shear strength (Error bars signify one standard deviation)

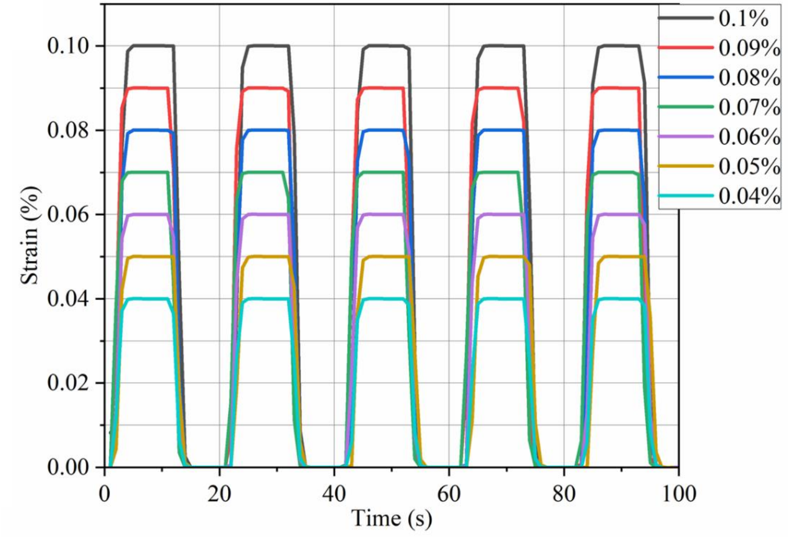
Accomplishments

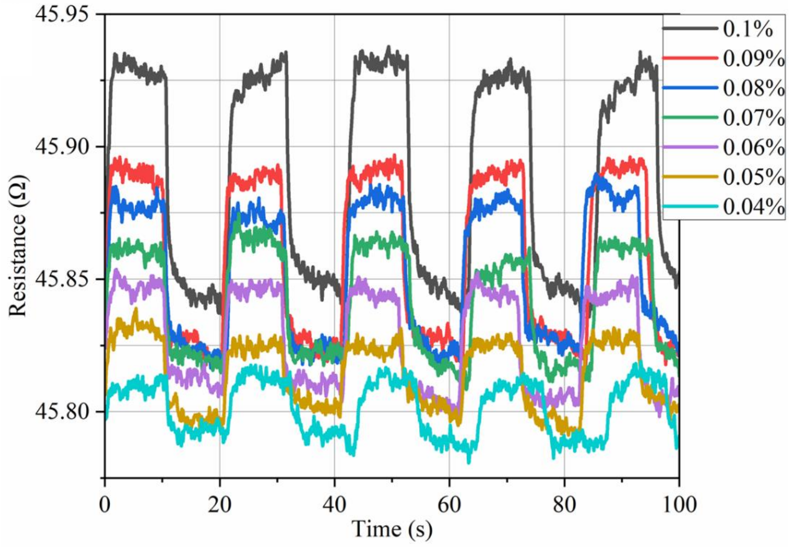
<u>Structural Health Monitoring</u>

- Out-of-plane through thickness electrical resistance was measured of a cantilevered beam during cyclic strain events
- **Gauge factor for each composite was measured over a range of strains to quantify the sensor sensitivity**



Average relative resistive change over a strain range





Structural health monitoring tests showing straining of a composite beam with corresponding electrical resistance changes

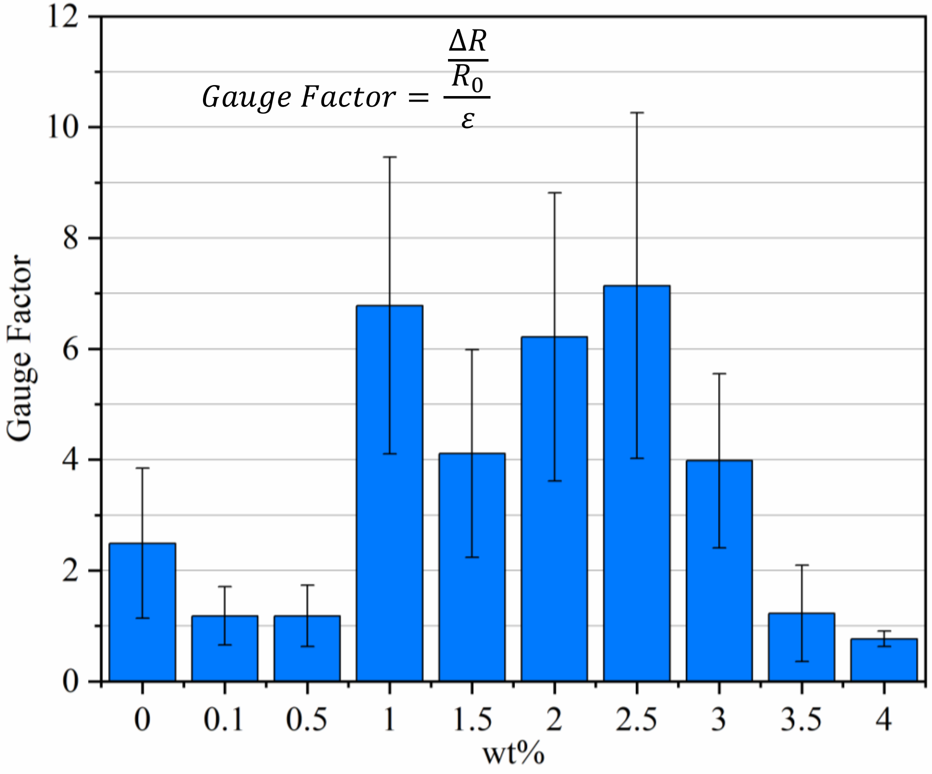
Accomplishments

Structural Health Monitoring

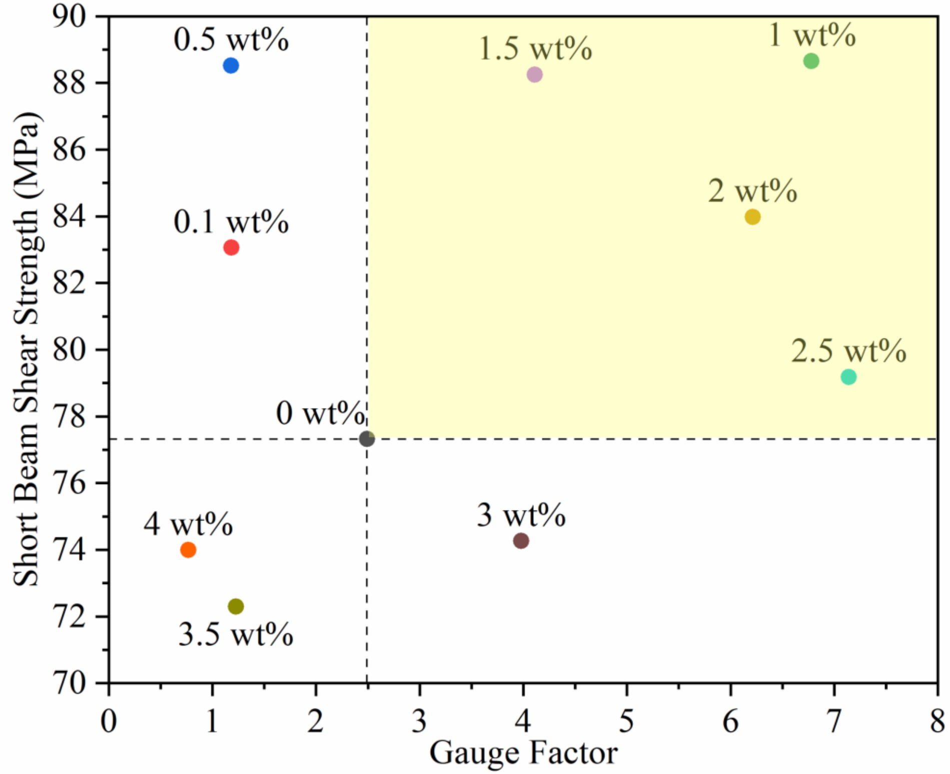
- Baseline gauge factor: 2.49 (0 wt% nanoparticles)
- Highest gauge factor: 7.14 (2.5 wt% nanoparticles)
- **Maximum gauge factor increase of 187% so milestone was achieved**

Milestone: Characterize the active sensing capabilities of the multifunctional composites (6/30/2020)

Criteria: Sensor testing in the dynamic mechanical analyzer should reveal at least a 20% improvement in sensitivity



Average gauge factor for each composite over the entire strain range



The average interlaminar shear strength versus the average gauge factor

Collaboration/Partner

Dronesat, LLC

- Designed and patented (patent pending) an Unmanned Aerial System (drone), powered from a ground based electrical infrastructure for sensor or cargo configurations
- Identify sensor capability that makes aware, timely information about critical components so actionable decisions can be quickly made about the airworthiness of vehicles.
- The ultimate result would reduce maintenance time by early detection of cracks or damage and the deterrence of the costly effects by failures which result in vehicle loss.

ORNL interns

- An undergraduate researcher from Virginia Tech (Susan Rankin)
- A post-Bachelor's intern from North Carolina State University as part of the GEM Fellowship Program (Mikayla Moody)

Interns holding TiO_2 nanoparticle coated carbon fiber spools

Susan Rankin (on left) and Mikayla Moody (on right)

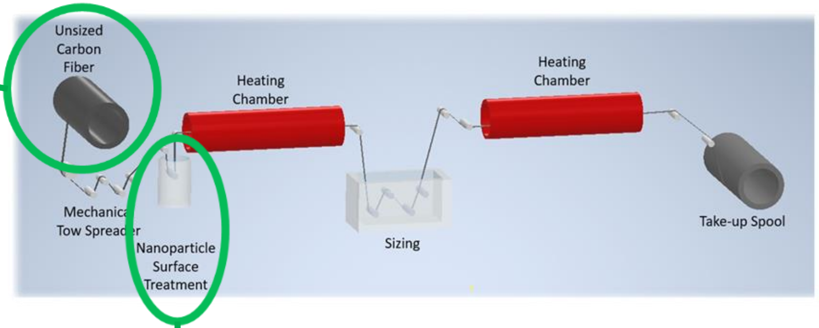
Proposed Future Research

Next milestones entail switching from active sensing to passive sensing:

- Coat fibers with ferroelectric nanoparticles
- Evaluate the interlaminar shear strength changes
- Measure the power output of composites in response to strain or vibration
  - Measuring voltage and current output as opposed to resistance
- Integrate wireless sensing
- Reinforce thermoplastic matrices with passive sensing fibers
- Fabricate hybrid composite, passive sensing composite

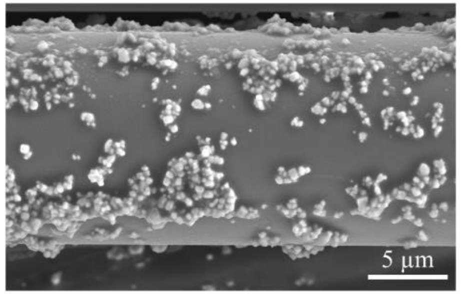
Modify coating process

Substitute carbon fiber with glass, aramid or basalt fibers



Substitute TiO_2 nanoparticles with $BaTiO_3$

$BaTiO_3$ nanoparticles on basalt fiber



Any proposed future work is subject to change based on funding levels.

Summary

- **Relevance:** Development a multifunctional fiber-reinforced composite with structural health monitoring capabilities and improved mechanical performance

- **Approach:** Nanoparticles deposited on the fiber surface via a continuous feed-through process

- **Technical Accomplishments:**
  - Demonstrated a roll-to-roll process to embed nanoparticles in the fiber sizing
  - Showed an interlaminar shear strength improvement of at least 10% (maximum increase was 14%) (Target date: Dec. 2019)
  - Demonstrated active sensing capabilities with at least a 20% improvement in sensitivity (actual improvement was 187%) (Target date: June 2020)

- **Future work:** Passive sensing with wireless communication

Technical Backup Slides

Milestones

Milestone/Deliverable Name/Description	End Date	Status
Fabricate multifunctional composites and perform mechanical testing	12/31/2019	**Complete**
Characterize the active sensing capabilities of the multifunctional composites	6/30/2020	**Complete**
Synthesize fibers with passive sensing capabilities	9/30/2020	On-Schedule
Fabricate a passive sensing, hybrid, multifunctional composite	12/31/2020	On-Schedule
Characterize the power generation of the hybrid, multifunctional composite in response to strain	6/30/2021	On-Schedule
Wireless sensing integration	9/30/2021	On-Schedule
Fabricate multifunctional composite structure with active sensing capabilities utilizing a thermoplastic matrix	12/31/2021	On-Schedule
Fabricate a passive sensing fiber-reinforced multifunctional composite using a thermoplastic matrix	6/30/2022	On-Schedule
Fabrication of a hybrid, multifunctional composite using a thermoplastic matrix	9/30/2022	On-Schedule

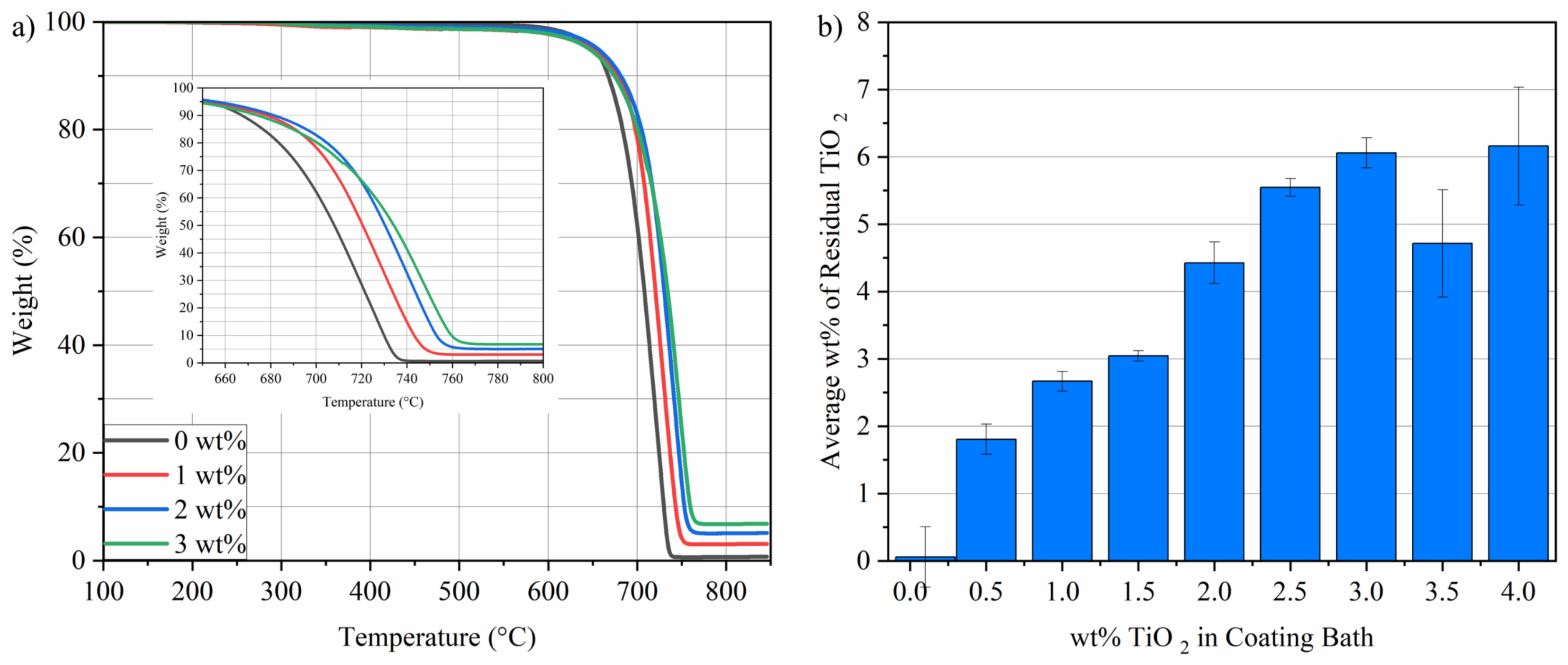
Go/No-Go Decisions

Name	Description	Date
Passive Sensing, Hybrid, Multifunctional Composite	Develop and fabricate a fiber-reinforced composite with at least two different fibers that act as a self-powered sensor	12/31/2020
Wireless Sensing Integration	Methods need to be developed to negate the need to physically adhere electrodes to the composite surface and to negate the need for wire leads to detect electrical changes	9/30/2021

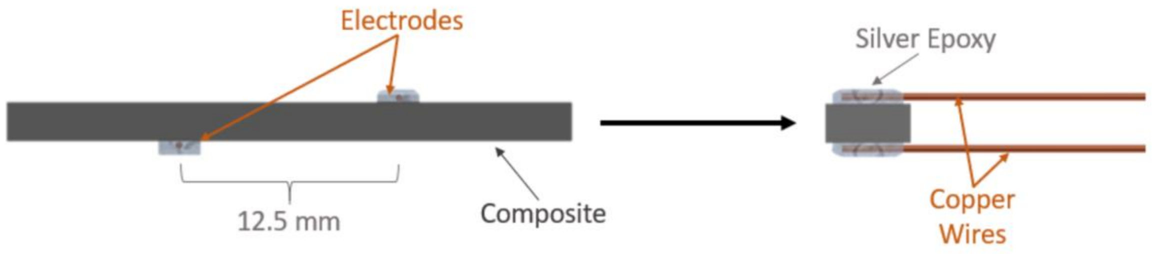
End goal: Fabrication of hybrid multifunctional composites with integrated wireless sensing for strain, damage and creep detection

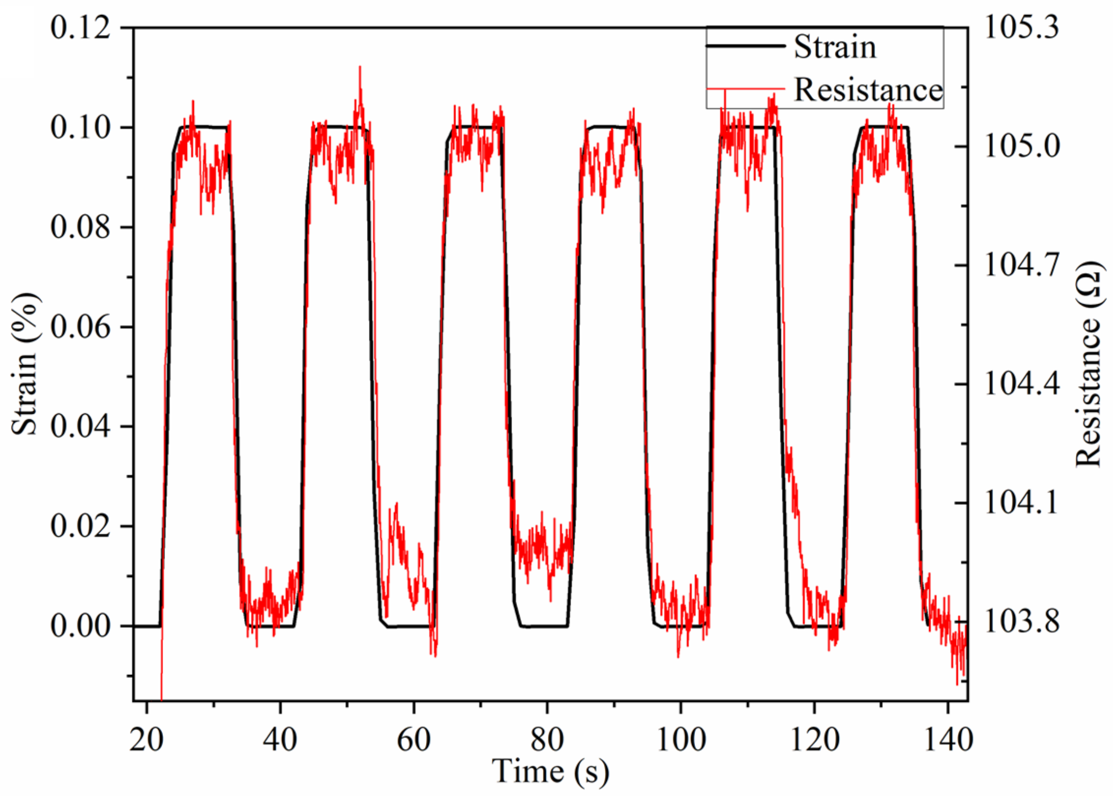
Technical Backup Slides

Thermogravimetric analysis



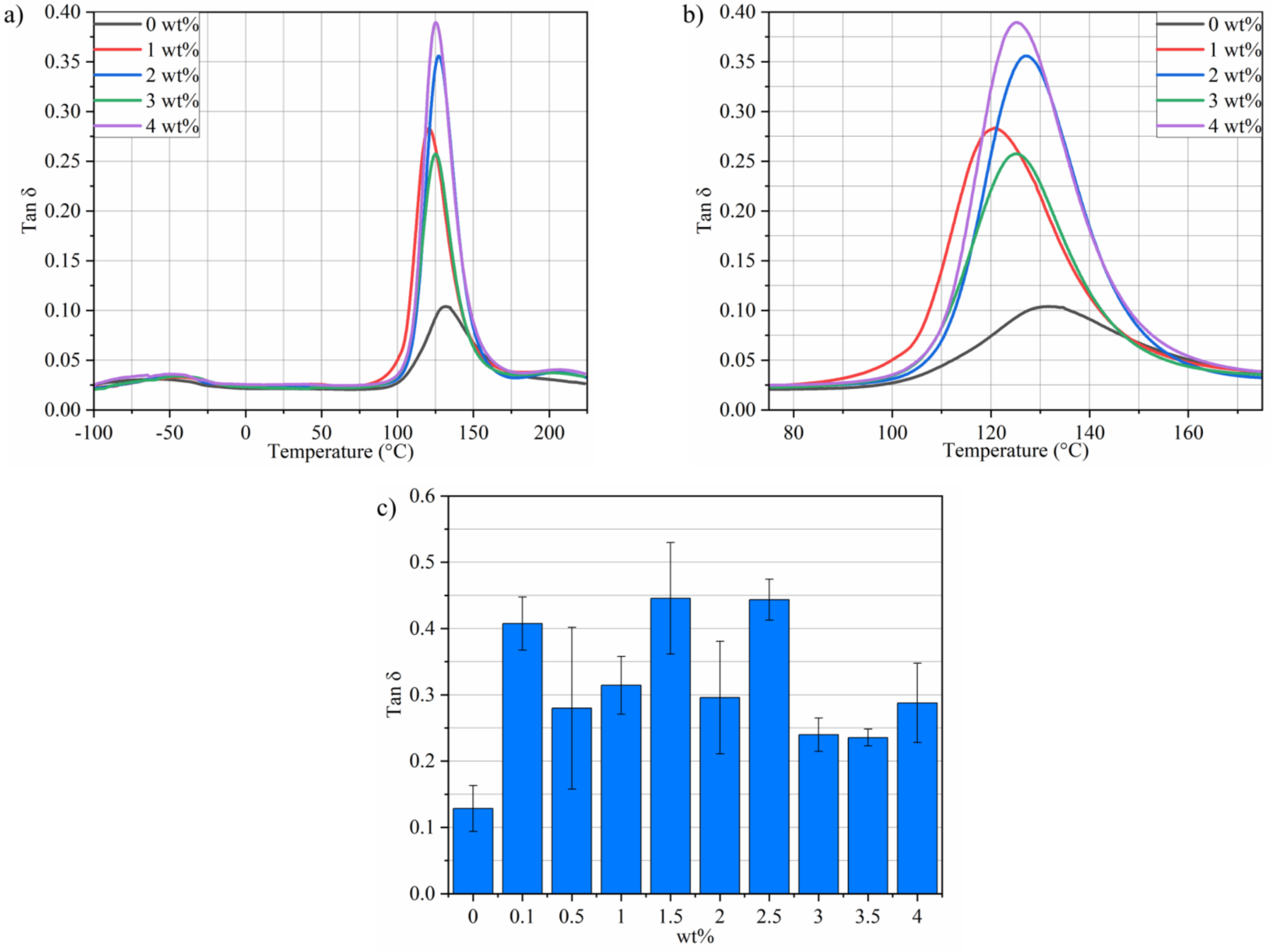
Technical Backup Slides





Technical Backup Slides

Dynamic Mechanical Analysis



Remaining Challenges and Barriers

- <u>Passive Sensing</u>
  - Deposition of ferroelectric nanoparticles on electrically insulating fibers
  - Power generated from the ferroelectric nanoparticles needs to be sufficient to produce a measurable signal
- <u>Wireless Sensing (by the end of FY21</u>)
  - This is the most high-risk, high-reward challenge for this project
  - Wireless sensing would negate the need for physical electrodes making these multifunctional composites feasible in real world applications
  - Extensive experimentation with the wireless communication is needed